(12) UK Patent Application (19) GB (11) 2 308 190 (13) A

(43) Date of A Publication 18.06.1997

(21) Application No 9623989.2

(22) Date of Filing 19.11.1996

(30) Priority Data
(31) 08570464 (32) 11.12.1995 (33) US

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(51) INT CL^6
G01V 1/40 1/44

(52) UK CL (Edition O)
G1G GMB
U1S S1248

(56) Documents Cited
US 4899844 A US 4833658 A US 4606014 A

(58) Field of Search
UK CL (Edition O) G1G GMB
INT CL^6 G01V 1/40 1/42 1/44
Online:-WPI

(54) **Acoustic reflection borehole logging apparatus**

(57) A tool 10 transmits acoustic signals at a frequency according to a predetermined diameter of the borehole 14, acoustic attenuation property of the formation and range of interest for the depth of investigation. A receiver array 20 comprises of eight receiver stations spaced vertically apart, each station having four hydrophones disposed circumferentially at ninety degree intervals. The signals reflected by the subsurface formation 16 are detected at each hydrophone and sent to signal storage 36, which also receives signals from a depth recorder 32 so as to associate the reflected signals with respective depth levels in the borehole. The stored data is processed to determine the distances of the reflecting structures, and an image of the underground formation surrounding the borehole is displayed on a VDU 38. The transmitters 18 are spaced from the receivers by differing distances so as to increase the range of depth of investigation.

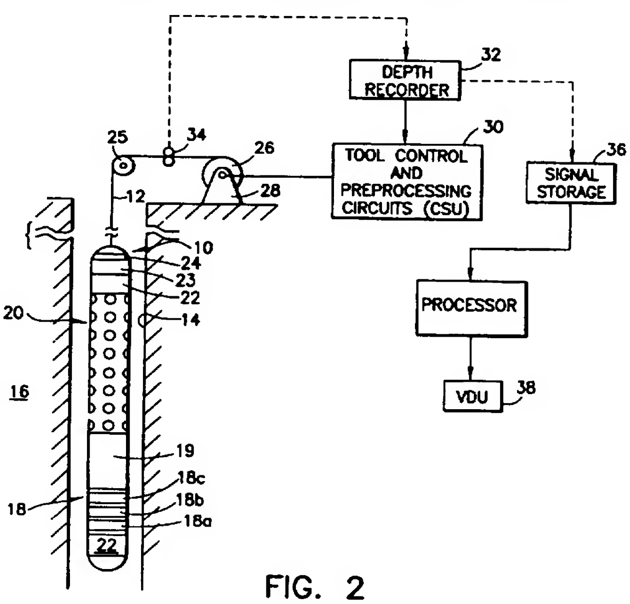

FIG. 2

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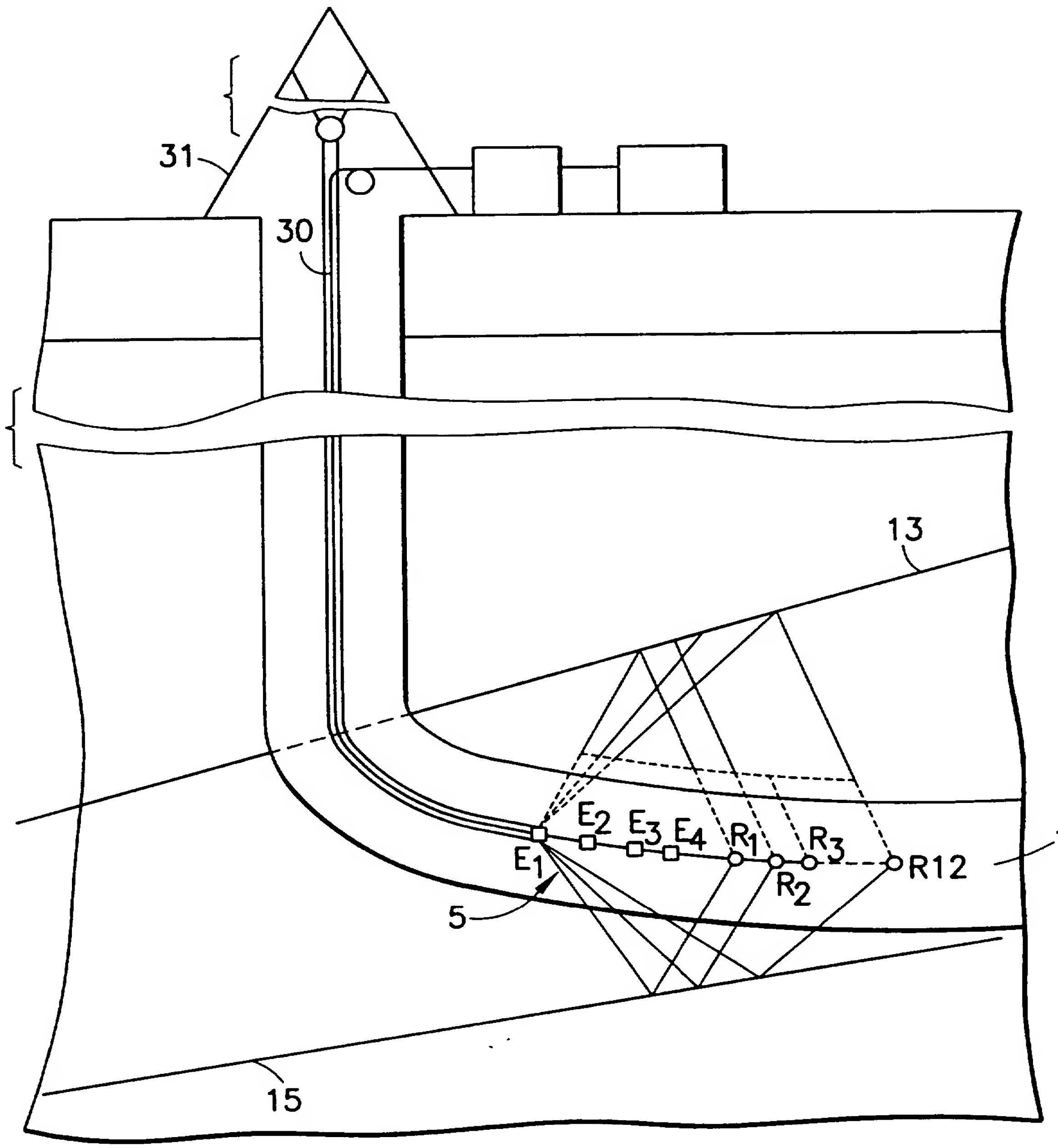


FIG. 1
PRIOR ART

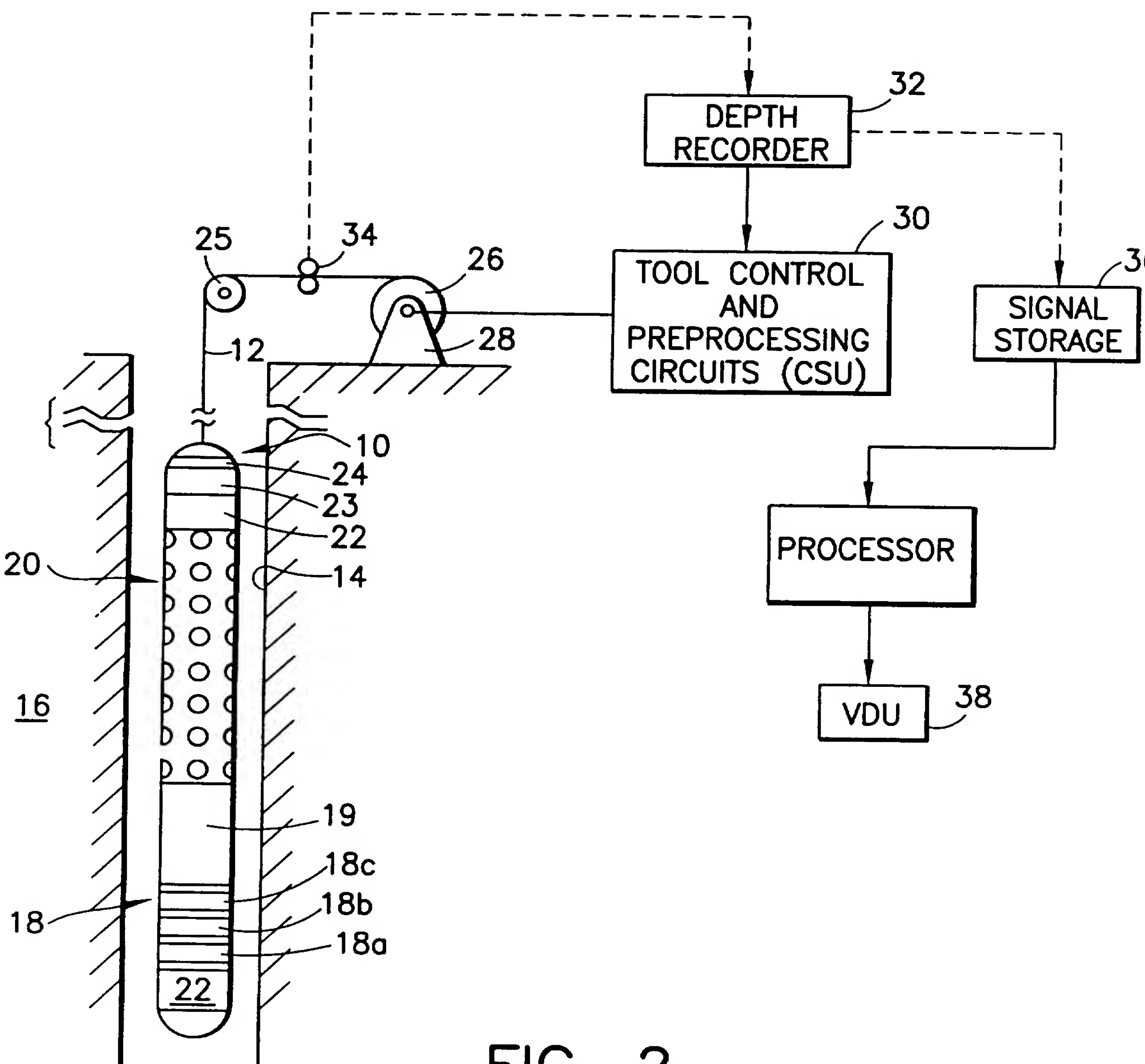

DEPTH RECORDER
32
TOOL CONTROL AND PREPROCESSING CIRCUITS (CSU)
30
SIGNAL STORAGE
36
PROCESSOR
VDU
38
25
34
26
28
12
10
24
23
22
20
14
16
19
18c
18b
18a
18
22

FIG. 2

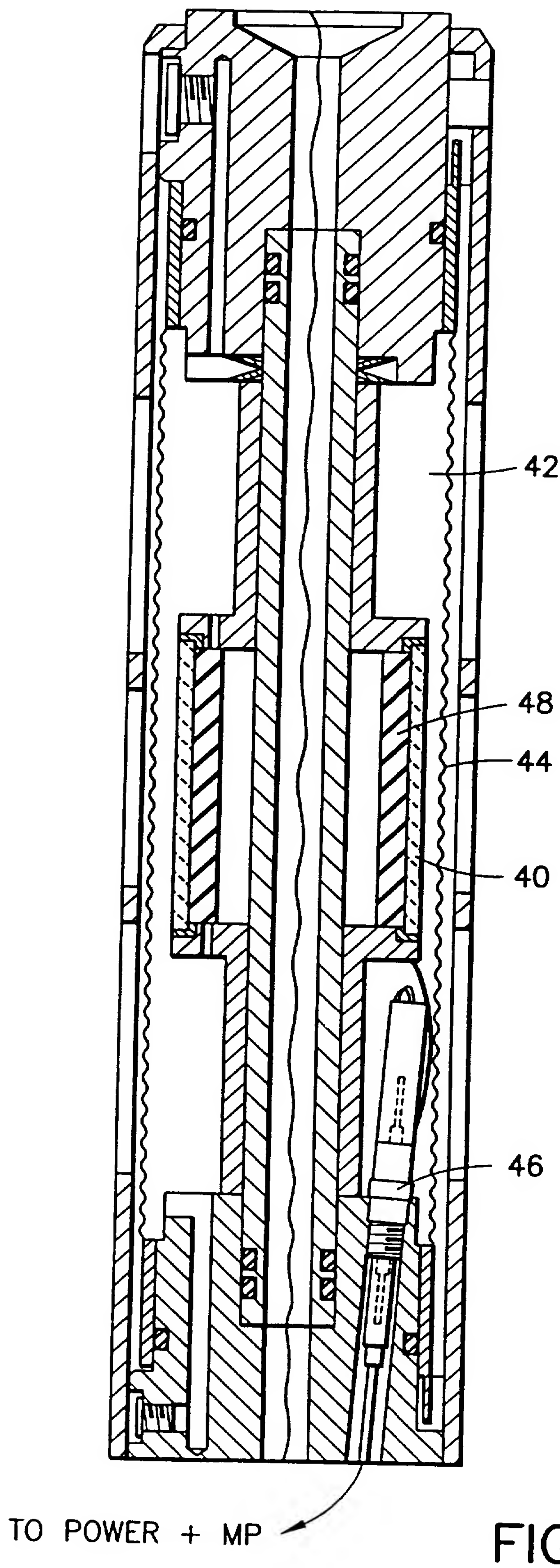
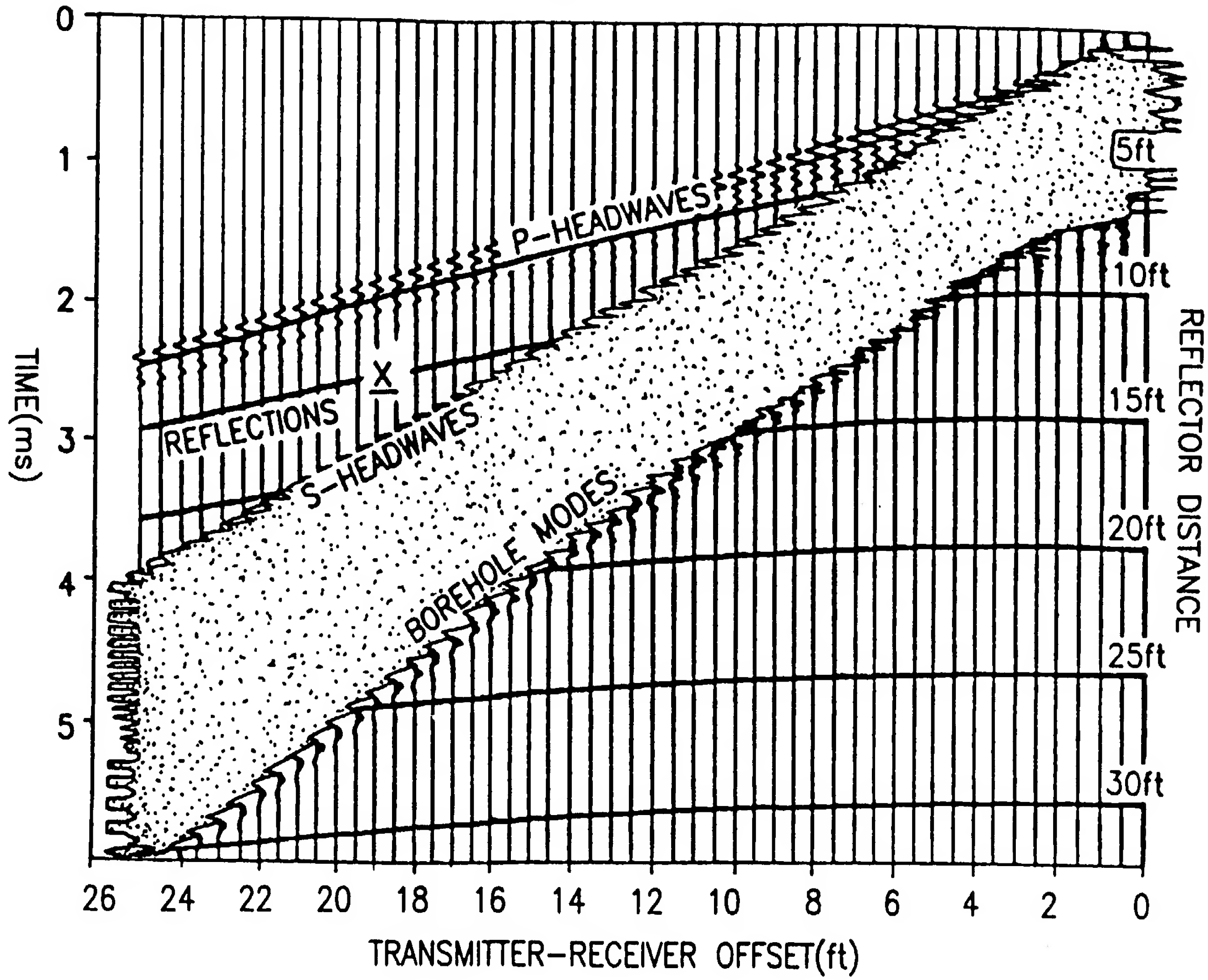


FIG. 3

FIG. 4


TIME(ms)
0
1
2
3
4
5
P-HEADWAVES
REFLECTIONS
X
S-HEADWAVES
BOREHOLE MODES
REFLECTOR DISTANCE
5ft
10ft
15ft
20ft
25ft
30ft
26
24
22
20
18
16
14
12
10
8
6
4
2
0
TRANSMITTER-RECEIVER OFFSET(ft)

2308190

METHOD AND APPARATUS FOR BOREHOLE ACOUSTIC REFLECTION LOGGING

FIELD OF THE INVENTION

The present application relates to a method and apparatus for use in borehole logging which involves detecting acoustic reflectors in the formation surrounding a borehole using acoustic signals generated and received in the borehole.

BACKGROUND OF THE INVENTION

Acoustic techniques for formation characterization are well known. All of these techniques involve transmitting an acoustic signal from a source to a receiver via the formation of interest. The frequency of the signal can vary from very low frequencies in seismic applications through sonic frequencies to ultrasonic frequencies, depending on the particular technique used. Most borehole logging involves the measurement of the time for a sonic signal to pass substantially directly from the source to the receiver via the formation at the borehole wall. Often the measurement is designed to record these direct arrivals and to exclude any signals due to reflections. Alternatively the received signals might be filtered to remove any signal due to reflections.

Seismic surveys generally involve the use of reflected acoustic signals, typically at very low frequencies, to detect structures below the earth's surface. The source of the signals and/or the detectors are usually located at the surface. Borehole seismic techniques place one of these inside the borehole.

In borehole acoustic reflection surveys, the measurements are made with acoustic transmitters and receivers placed in the same borehole. This configuration is best suited for recording reflected wave fields from acoustic reflectors that have small angles with the boreholes axis. For example, near-vertical fractures, faults and salt-dome flanks are good borehole reflection targets for near-vertical wells. Near-horizontal bed boundaries, fluid contact interfaces (gas/oil or oil/water) and

stringers inside reservoirs are good targets for highly-deviated and horizontal wells. The desired events (reflections) in borehole reflection surveys are the waves that propagate from the borehole to the reflector in the formation and back to the borehole. A significant portion of the acoustic energy from the transmitter, however, propagates directly to the receiver array. These direct waves include compressional- and shear-headwaves, tube waves (Stoneley waves), fluid and borehole modes and various casing modes if the well is cased. The direct waves may also include various tool modes that propagate along the tool body. In acoustic logging applications some of these direct waves, e.g. the headwaves and Stoneley waves, are used to log formation properties. In reflection survey applications, however, they are unwanted. The direct waves are typically much larger than reflections.

Reflection imaging around a well using downhole acoustic measurements has been proposed previously, in particular for use in horizontal wells for determining the position of the top or bottom of a reservoir in relation to the borehole. US Patent No. 4,833,658 discloses a method of processing signals to determine the positions of reflectors around a horizontal well. Figure 1 shows the system described in the '658 patent. A tool 5 comprises four transmitters E_1 - E_4 and twelve receivers R_1 - R_{12} positioned in a horizontal borehole 1 at the end of a drill string 30 coupled to a drilling derrick 31 at the surface. The transmitters are separated from each other by a constant interval equal, for example, to 0.25m, and the receivers are separated from each other by a constant interval equal, for example, to 1m. The separation of the closest transmitter and receiver is sugested as 1m. The length of the tool is selected to be at most equal to the distance between the borehole and the most distant reflecting structure (interface 13, 15) of interest. The tool 5 is logged along the borehole 1 and the transmitters E operate to produce acoustic signals with frequencies in the range of 5,000 - 10,000 Hz and the receivers R receive both direct and reflected waves. The received signals are analysed to determine the average propagation velocities of the direct (refracted) and reflected waves. A time section is determined from the signals corresponding to the reflected waves and the time section is converted to a depth section by means of the average propagation velocity of the reflected waves. The position of the reflecting interface is determined

from this depth section. While the approach and parameters suggested in the '658 patent will work in some cases, there are many cases in which they will not. The '658 patent does not recognize this and provides no teaching which would suggest appropriate modifications to the technique to allow it to work in all circumstances.

It is an object of the present invention to provide a technique for reflection acoustic logging in which the problems identified above are less significant and which will allow measurements to be made in a wider range of formations.

SUMMARY OF THE INVENTION

A method of imaging formations surrounding a borehole according to the invention comprises determining the diameter of the borehole; determining an acoustic attenuation property of the formations; determining a range of interest for depth of investigation into the formation from the borehole; positioning a tool in the borehole, the tool having at least one monopole transmitter and at least one acoustic receiver separated therefrom by a distance selected according to the range of interest of the depth of investigation; transmitting, with the at least one monopole transmitter, acoustic signals into the formation at a frequency selected according to the diameter of the borehole, the acoustic attenuation property of the formation and the range of interest for depth of investigation; receiving the acoustic signals at the at least one receiver which have been reflected from structures within the formation; analyzing the received acoustic signals to determine the distances of the reflecting structures from the borehole; and generating an image of the position of the reflecting structures with respect to the borehole on the basis of the determined distances.

Apparatus according to the invention for imaging formations surrounding a borehole, comprises a tool body; at least one monopole transmitter positioned on the tool body for transmitting acoustic signals into the formation at a frequency selected according to borehole diameter, a predetermined acoustic attenuation property of the formation and the range of interest for depth of investigation; at

least one acoustic receiver positioned on the tool body and separated from the at least one transmitter by a distance selected according to a range of interest of depth of investigation, the at least one receiver receiving the acoustic signals which have been reflected from structures within the formation; means for analyzing the received acoustic signals to determine the distances of the reflecting structures from the borehole; and means for generating an image of the position of the reflecting structures with respect to the borehole on the basis of the determined distances.

By taking into account the attenuative properties of the formation, the effect of borehole diameter and the desired depth of investigation, it is possible to configure and operate the tool so as to optimize performance over a range of conditions which has not been previously possible.

One particularly preferred use of the invention is the imaging of the formation around the borehole, especially when the borehole is horizontal. The reflected signals can be analyzed to identify the position of reflecting structures such as reservoir boundaries, salt domes or fractures in the formation relative to the borehole and the positions can be represented as an image which can be used to characterize the formation.

It is preferred to use one or more transmitters and an array of receivers. While a single transmitter can be used in certain circumstances, the range of depths of investigation is often limited. Thus the use of more than one transmitter is preferred so as to provide sufficient range in the transmitter to receiver spacing to provide a good range of depths of investigation. Two or three transmitters are believed to provide the best compromise between range and the physical and operational requirements of a borehole tool. Axial receiver arrays provide increased reflected event amplitudes with respect to the tube waves. A typical receiver array will comprise eight axial receiver stations with each station separated by an equal distance, for example six inches. Azimuthal receiver arrays allow the determination of the azimuthal position of reflecting bodies in the formation with respect to the borehole. Four hydrophones disposed around the tool axis at each receiver station are preferred. By recording the waveforms at each hydrophone at each station,

signals can be compared and the direction from which the reflection has arrived can be determined.

The frequency of the transmitted acoustic signals is selected according to borehole diameter, the nature of the formation and the desired range of investigation. Frequencies can range from 100Hz or lower for long range imaging in an attenuative medium to 20kHz or higher for short range, high resolution imaging in a non-attenuative medium. For typical monopole sources suitable for the present invention, the frequency is usually in the range of 1 kHz to 15 kHz.

In order to prevent part of the direct tube wave signal from propagating past the receiver (or transmitter) and reflecting back to the receiver from structures inside the borehole so as to interfere with the reflected signals from the formation, it is preferred to used one or more attenuators positioned in the tool string. These are preferably of the form described in co-pending application no. 08/527,736 (incorporated herein by reference).

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a general schematic view of a prior art borehole reflection imaging system;
Figure 2 shows a schematic view of a borehole reflection imaging system according to the invention;
Figure 3 shows a monopole source for use in the invention; and
Figure 4 shows a plot of the headwave arrivals limiting the detection of reflected signals.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Figure 2 shows a schematic view of a borehole acoustic reflection imaging system according to one embodiment of the present invention. A sonic reflection imaging tool 10 is shown lowered on an armored multiconductor cable 12 into a borehole 14, which can be cased or uncased, to make sonic measurements for imaging of the

subsurface formation 16. In cases where the borehole is deviated from vertical, especially when horizontal, the cable 12 can be run inside drill pipe or tubing such as coil tubing which allows the tool 10 to be pushed into the well when gravity is insufficient or unable to move the tool to the depth of interest. The tool 10 is provided with transmitters 18a, 18b, 18c and a receiver array 20 immediately adjacent thereto which are described in more detail in US Patents Nos. 4,850,450, 5,036,945 and 5,043,952 all of which are incoporated herein by reference. The separation of the transmitter and receiver array is achieved by using a spacing body 19 which incoporates a sonic isolation joint such as is described in US Patent No. 5,036,945. The length of the spacing body 19 is selected according to the range of interest of the depth of investigation. For example, a typical length of a spacing body is 32' and the overall distance from the farthest transmitter 18a to the farthest extent of the receiver array 20 is 43'. One or more tube wave attenuators 22 can be provided at both ends of the transmitter/receiver array section to reduce interfering effects of reflected tube waves in the borehole. These attenuators and their function are described in detail in co-pending application no. 08/527,736, incorporated herein by reference. Such attenuators can also be used between transmitters and the receiver array if required. An orientation device (e.g GPIT tool of Schlumberger including magnetometers and accelerometers) 23 and a telemetry cartridge 24 complete the downhole tool.

The tool 10 is adapted from movement up and down borehole 14, and as the tool 10 is moved, the transmitters 18 periodically generate sonic signals. The generated sonic signals travel through the borehole and/or through the formation where they are reflected by underground structures, and the receivers in the receiver array 20 typically detect some energy which results from the generated signals. The mechanism for moving the tool 10 in the borehole includes the cable 12 which extends to the sheave wheel 25 at the surface of the formation, and then to a suitable drum and winch mechanism 26 which raises and lowers the tool 10 in the borehole as desired. Electrical connection between transmitter array 18 and receiver array 20 on the one hand, and the surface equipment on the other hand, is made through suitable a multi-element slipring and brush contact assembly 28 associated with the drum and winch mechanism 26. A unit 30 contains tool control and pre-processing circuits which send electrical signals to the tool 10 and receive other electrical signals (sonic logs) therefrom via cable 12 and assembly 28. The unit 30 cooperates with a depth recorder 32 which derives depth level signals from a depth

measuring wheel 34 so as to associate the signals from receiver array 20 with respective depth levels in borehole 14. The outputs of the receiver array 20, after optional pre-processing in unit 30, are sent to signal storage 36, which can also receive signals from or through depth recorder 32 so as to associate sonic receiver outputs with respective depth levels in the borehole 14. Storage 36 can store the outputs of the receiver array 20 in the form of digital sonic log measurements. Storage 36 can comprise a magnetic storage device such as a disk or tape, and/or other storage media such as semiconductor or equivalent memory circuits. The stored digital data can then be processed to provide an image of the underground formation surrounding the borehole either as a printed image or displayed on a VDU 38. Kirchhoff-type migration of the data, such as is commonly used in seismic processing, is used to derive the image of the reflecting structures around the borehole.

Each transmitter 18a, 18b, 18c comprises a monopole source which is substantially as described in US Patent No. 5,043,952 (incorporated herein by reference) and shown in Figure 3. These are substantially the same as the monopole source used in conventional sonic logging applications. The source comprises piezo-ceramic cylinder 40 held in an oil filled cavity 42 defined by a corrugated container 44, the corrugations of which allow for differential changes in volume between the mud outside and the oil inside the corrugated container. A power amplifier is attached to the piezo-ceramic cylinder 40 via an electrode 46 for polling the cylinder radially. The electrode 46 is attached to the inner and outer surfaces of the piezo-ceramic cylinder 40 for applying a voltage to the cylinder which causes it to expand in length and radius, thereby causing a volumetric expansion resulting in the generation and propagation of compressional waves into the borehole, and of both compressional waves and shear waves into the formation.

In order to radiate acoustic energy efficiently, the transmitters 18 are designed to operate near geometrical resonances which unavoidably will ring for a long time. A damping mechanism has been introduced to stop this ringing which comprises a rubber-tungsten backing material 48 for the acoustic signal source to provide a good impedance match as well as damping to the attached structure. The rubber-

tungsten backing also prevents the additional fluid mode excitation when the transducer is immersed in the fluid. The rubber- tungsten composite comprises a butyl rubber skeleton loaded with tungsten powder. The impedance and attenuation of the backing will depend on the percentage of tungsten, the degree of compaction of the powder and the degree of vulcanization as well as adherence of the rubber onto the powder.

In Figure 2 three transmitters are shown although it will be appreciated that the invention can be performed with more or less transmitters than this. For example, two transmitters can give a range for the depth of investigation of the order of 30' which would be adequate in certain circumstances. The spacings between the transmitters has been selected to achieve a wide range of depths of investigation. The separation between transmitter 18a and 18b is about 4' and between transmitter 18b and 18c is about 3'6". The considerations for selecting the best spacing for given circumstances are discussed in more detail below. A hydrophone is positioned in transmitter 18c for the purpose of monitoring the output of the source. This hydrophone optionally can also be used as a short spaced receiver. The spacing between transmitter 18c and the receivers can be increased to provide an increased depth of investigation. Alternativley, the spacings between the transmitters can be increased to provide multiple depths of investigation.

The receiver array 20 comprises eight receiver stations spaced 6" apart vertically, each station having four hydrophones disposed circumferentially at 90^0 intervals about the tool making a total of 32 hydrophones. This array is described in detail in US Patent No. 5,036,945. The signals detected at each hydrophone are recorded separately and the signals received by the array analyzed to provide the direction and distance of reflecting structures from the borehole.

The orientation device 23 allows the position and orientation of the tool in the borehole to be determined. Accordingly, the direction from which the reflections arrive can be determined and it is possible to determine whether a reflector is above or below the borehole in a horizontal well, or its direction relative to the borehole in a vertical well.

The imaging range (window) of reflectors away from the borehole is limited due to several reasons. First, in most cases this window, shown as region X in Figure 4, is terminated by the shear-headwave and tube waves which are typically much larger than the reflected compressional waves. For a reflector parallel to the borehole axis, the arrival time of a compressional-wave reflection is approximately given by

$$time_{ref} \approx \frac{1}{v_p}\sqrt{4range^2 + offset^2} \qquad (1)$$

where *range* is the distance of the reflector from the borehole, *offset* is the transmitter-receiver offset, and v_p is the compressional-wave speed. The direct shear wave arrival times, defining the end of the imaging window, are given by

$$time_{dir} \approx offset / v_s \qquad (2)$$

The maximum distance from the borehole, that can be imaged with the large-offset approach, is obtained by setting equation (1) equal to (2) and solving for range, giving

$$range_{max} \approx 0.5 offset\sqrt{\left(\frac{v_p}{v_s}\right)^2 - 1} \qquad (3)$$

For example, for a typical value of $\frac{v_p}{v_s} = 1.73$, the maximum range is given by $range_{max} \approx 0.7 offset$. In more general form, v_s above represents the velocity of the first dominating direct wave following the compressional headwave. There is also a minimum range limit. Reflections from very-close reflectors can be masked by the ringing of the direct waves. The duration of the ringing is inversely proportional to the bandwidth of the direct wave, and it very much depends on the acquisition parameters such as the spectral output of the transmitter. Resonance frequencies of the interfering direct waves should be avoided to reduce the ringing duration. For example, for a formation with compressional velocity of 10,000 ft/sec (100 μsec/ft),

the minimum range is approximately 5 ft for 1 kHz bandwidth, and 10 ft for 500 Hz bandwidth.

The second reason for the range limitation is the rapid decrease in reflected-wave amplitudes due to geometrical spreading and attenuation. Amplitude decrease due to geometrical spreading is approximately proportional with the total distance traveled by, or the arrival time of, the reflected event. The amplitude decrease at large offsets due to attenuation can be even more significant than the geometrical spreading. The dependence of the reflected-wave amplitudes on attenuation, frequency and distance is given by

$$amplitude_{ref} \propto \exp\left\{-\frac{\pi f}{v_p Q} d\right\} \qquad (4)$$

where f is the frequency, d is the reflection ray path, and Q is a number representing attenuation properties of a medium. Q values can vary significantly, from 5 for a very attenuative medium to 100 for an ideally non-attenuative medium. The above equation shows that amplitude decrease due to attenuation increases exponentially with the propagation path length of the reflected event which increases with the offset. The frequencies employed can range from 100 Hz (or lower) for long-range imaging in attenuative medium, to 20 kHz (or higher) for short-range, high-resolution imaging in non-attenuative medium.

The duration of each pulse from the source and the number of measurements made at the receiver array for each pulse depends on the ability of the system to record data. It may be necessary or desirable to use a number of pulses and record the data from different sets of hydrophones for each pulse which are then stacked to ensure that measurements are made for all combinations of transmitter and receiver in the array. This can be done while moving the tool through the borehole a normal logging speeds.

The signals received by each of the hydrophones are treated in essentially the same manner as signals received by hydrophones in a seismic array and an image is

produced using the same techniques. Thus an image can be produced along the borehole axis (depth axis) and azimuthally around the borehole. By recording complete waveforms at each azimuthal hydrophone position, it becomes possible to determine the time at which a given reflected signal is detected at each position and hence the direction from which it has arrived. For example,in a horizontal borehole, if a given reflection is detected first at the uppermost hydrophone followed by detection at lower hydrophones, the reflecting structure can be indentified as being above the borehole, and vice versa for a reflector below the borehole.

The apparatus descibed above for making reflection measurements in a borehole might also be used to obtain conventional refracted data for evaluation of formation properties in a known manner, in which measurements considered unneccessary for this invention such as headwave measurements, might be used to determine formation parameters. Also, the general approach described above can be applied to cross-well imaging provided that the wells are sufficiently close together.

The present invention is applicable to both wireline and logging-while-drilling applications. In LWD applications, the apparatus forms part of a bottom hole assembly above a drill bit, in the manner of previously proposed LWD sonic logging tools.

CLAIMS

1. A method of imaging formations surrounding a borehole, comprising:
   a) determining the diameter of the borehole;
   b) determining an acoustic attenuation property of the formations;
   c) determining a range of interest for depth of investigation into the formation from the borehole;
   d) positioning a tool in the borehole, the tool having at least one monopole transmitter and at least one acoustic receiver separated therefrom by a distance selected according to the range of interest of the depth of investigation;
   e) transmitting, with the at least one monopole transmitter, acoustic signals into the formation at a frequency selected according to the diameter of the borehole, the acoustic attenuation property of the formation and the range of interest for depth of investigation;
   f) receiving the acoustic signals at the at least one receiver which have been reflected from structures within the formation;
   g) analyzing the received acoustic signals to determine the distances of the reflecting structures from the borehole; and
   h) generating an image of the position of the reflecting structures with respect to the borehole on the basis of the determined distances.

2. A method as claimed in claim 1, wherein the frequency is selected so as to avoid the resonant frequency of headwaves travelling from the transmitter to the receiver.

3. A method as claimed in claim 1, wherein the frequency is selected to optimize coupling of reflected acoustic signals into the borehole.

4. A method as claimed in claim 1, wherein acoustic signals of more than one frequency are transmitted and detected.

5. A method as claimed in claim 1, comprising transmitting acoustic signals from a plurality of transmitters, which are spaced from the at least one receiver by differing distances so as to increase the range of depth of investigation

6. A method as claimed in claim 1, comprising receiving reflected acoustic signals with an array of receivers.

7. A method as claimed in claim 1, comprising receiving reflected signals at a purality of azimuthal positions around the tool.

8. A method as claimed in claim 7, further comprising analyzing the received signals to determine the direction of the reflecting structures from the borehole.

9. A method as claimed in claim 7, wherein complete waveforms are recorded at each azimuthal position.

10. Apparatus for imaging formations surrounding a borehole, comprising:

a) a tool body;

b) at least one monopole transmitter positioned on the tool body for transmitting acoustic signals into the formation at a frequency selected according to borehole diameter, a predetermined acoustic attenuation property of the formation and the range of interest for depth of investigation;

c) at least one acoustic receiver positioned on the tool body and separated from the at least one transmitter by a distance selected according to a range of interest of depth of investigation, the at least one receiver receiving the acoustic signals which have been reflected from structures within the formation;

d) means for analyzing the received acoustic signals to determine the distances of the reflecting structures from the borehole; and

e) means for generating an image of the position of the reflecting structures with respect to the borehole on the basis of the determined distances.

11. Apparatus as claimed in claim 10, wherein the acoustic receiver comprises an axial array of hydrophones.

12. Apparatus as claimed in claim 10, wherein the acoustic receiver comprises a radial array of hydrophones

13. Apparatus as claimed in claim 10, wherein at least two axially spaced transmitters are provided on the tool body.

14. Apparatus as claimed in claim 10, wherein the frequency of the acoustic signals is in the range 1 kHz to 15 kHz.

15. Apparatus as claimed in claim 12, wherein the radial array comprises hydrophones disposed at 90° intervals around the tool body.

16. Apparatus as claimed in claim 15, wherein each hydrophone records substantially complete waveforms.

17. Apparatus as claimed in claim 16, wherein the means for analyzing the received acoustic signals analyzes the waveforms from each hydrophone so as to determine the direction of the reflecting structure from the borehole.

18. Apparatus as claimed in claim 10, further comprising an acoustic receiver positioned at the at least one transmitter.

19. Apparatus as claimed in claim 11, wherein the axial array comprises eight substantially equidistantly spaced receiver stations.

20. Apparatus as claimed in claim 19, wherein each receiver station comprises four hydrophones disposed at 90° intervals around the tool body.

The Patent Office

15.

Application No: GB 9623989.2
Claims searched: 1-20

Examiner: Matthew Nelson
Date of search: 11 February 1997

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): G1G (GMB)

Int Cl (Ed.6): G01V (1/40, 1/42, 1/44)

Other: Online :-WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
A	US 4899844	(KATAHARA et al). See col 2, lines 13-18 & lines 29-45; col 8, lines 15-26.	
X	US 4833658	(STARON). See whole document.	10 at least
A	US 4606014	(WINBOW). See col 8, lines 36-40	

X Document indicating lack of novelty or inventive step	A Document indicating technological background and/or state of the art.
Y Document indicating lack of inventive step if combined with one or more other documents of same category.	P Document published on or after the declared priority date but before the filing date of this invention.
& Member of the same patent family	E Patent document published on or after, but with priority date earlier than, the filing date of this application.